

# The NO $\nu$ A experiment

WINP 2015

Christopher Backhouse

California Institute of Technology

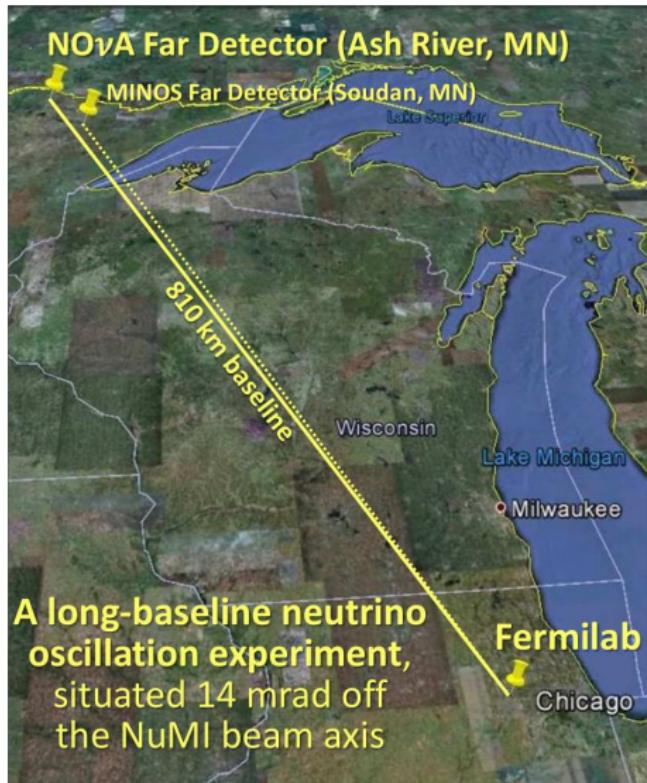
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# NO $\nu$ A physics goals

$\nu_\mu \rightarrow \nu_e$

- Measure  $P(\nu_\mu \rightarrow \nu_e)$



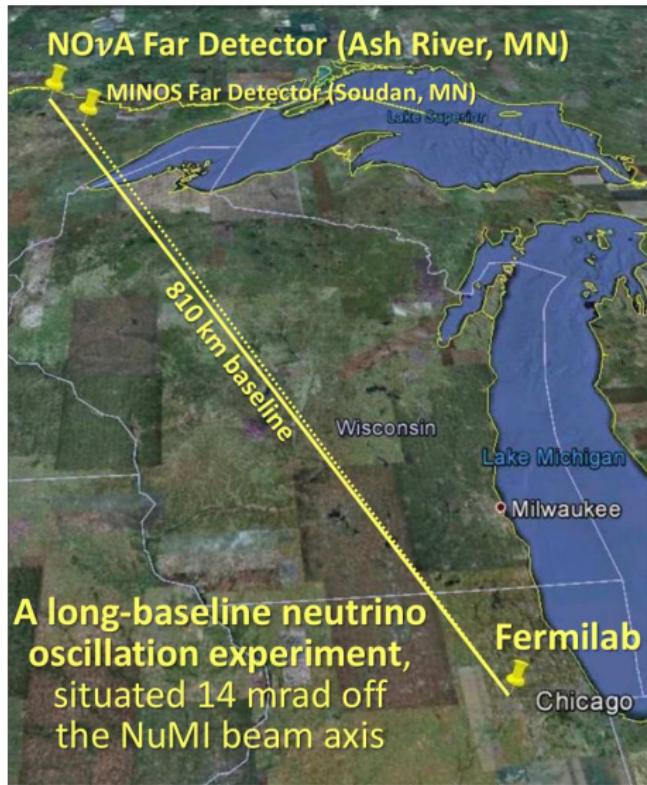
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- ▶ Measure  $P(\nu_\mu \rightarrow \nu_e)$

$\nu_\mu \rightarrow \nu_\mu$

- ▶ Precision measurements of  $|\Delta m_{\text{atm}}^2|$  and  $\theta_{23}$
- ▶ Could exclude maximal mixing



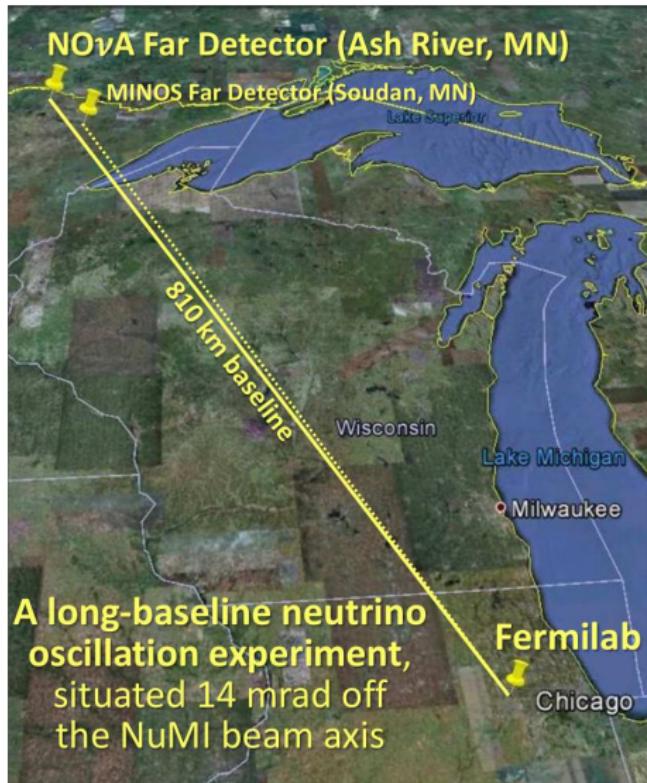
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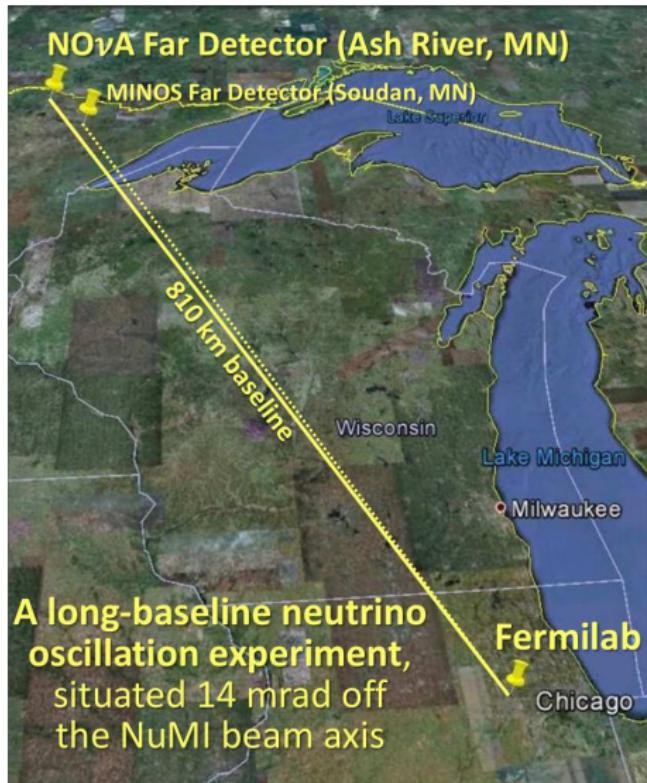
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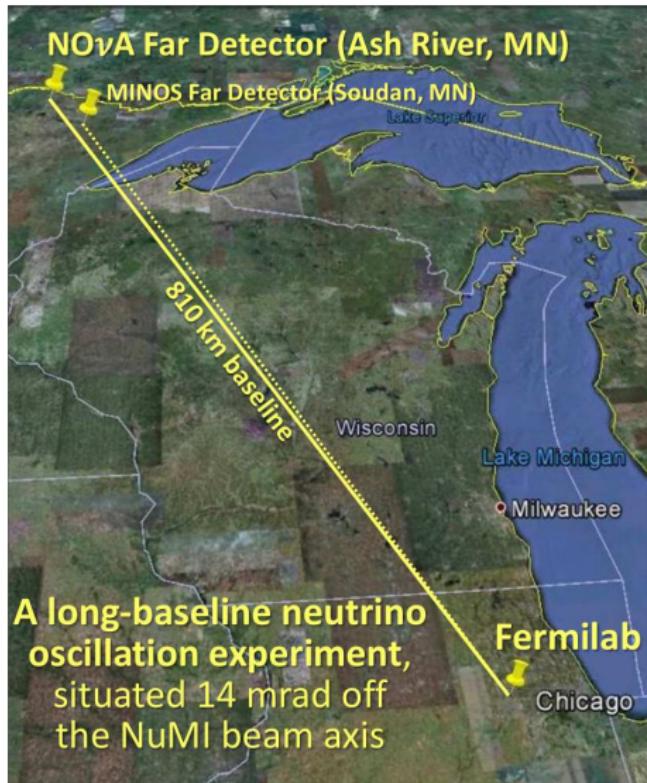
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$\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- ▶ Measure  $P(\nu_\mu \rightarrow \nu_e)$
- ▶ Determine the  $\theta_{23}$  octant
- ▶ Determine the mass hierarchy
- ▶ Search for  $\delta_{CP} \neq 0$

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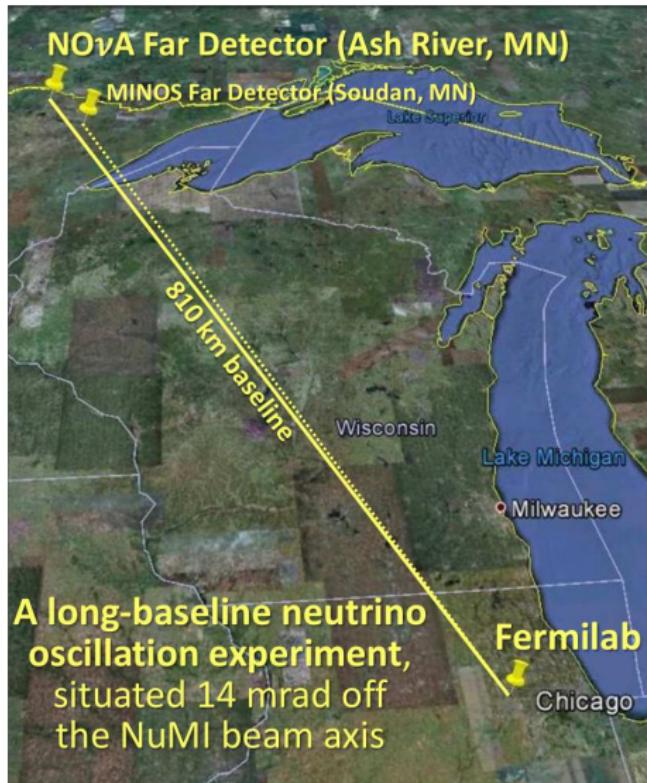
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- ▶ Precision measurements of  $|\Delta m_{\text{atm}}^2|$  and  $\theta_{23}$
- ▶ Could exclude maximal mixing

Plus...

- ▶ Cross-sections from the ND
- ▶ Steriles, supernovae, exotica



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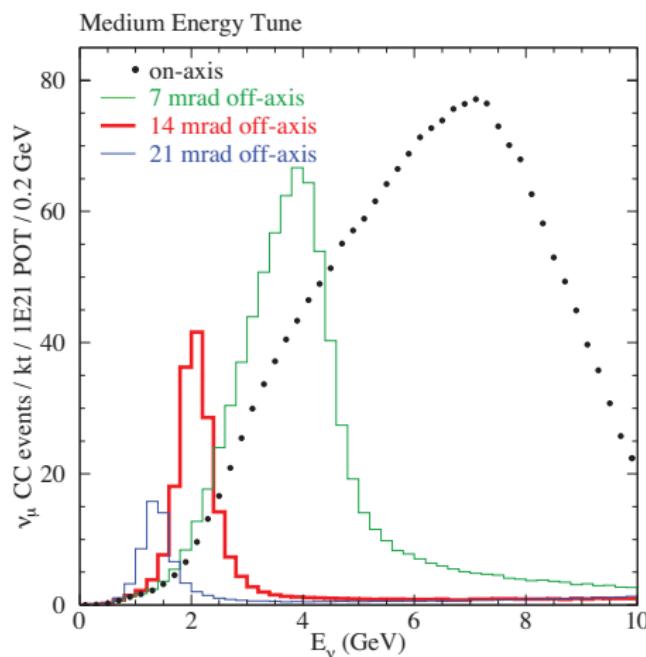
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$\nu_\mu \rightarrow \nu_\mu$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- ▶ Precision measurements of  $|\Delta m_{\text{atm}}^2|$  and  $\theta_{23}$
- ▶ Could exclude maximal mixing

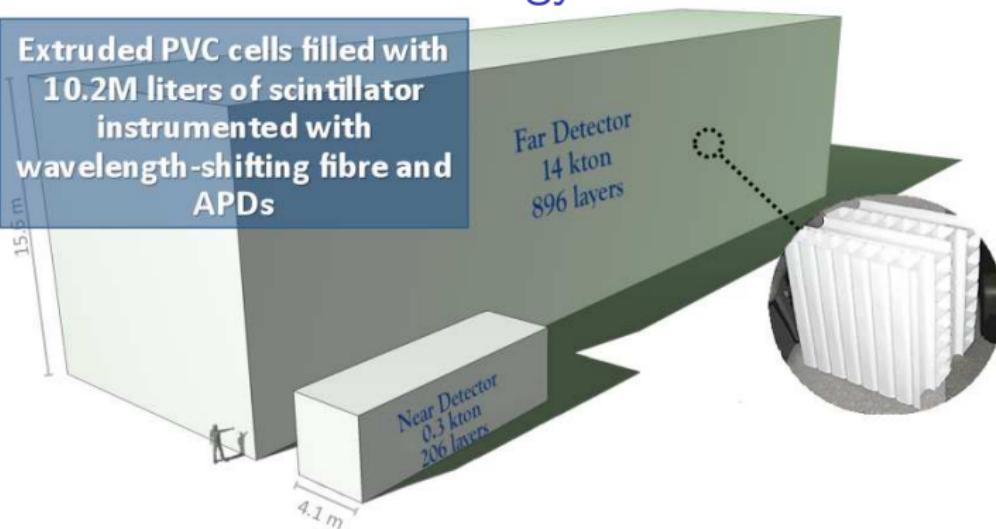
Plus...

- ▶ Cross-sections from the ND
- ▶ Steriles, supernovae, exotica

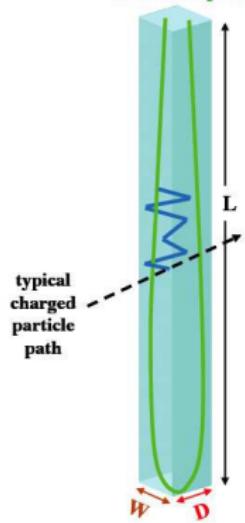


# NO $\nu$ A detector technology

Extruded PVC cells filled with  
10.2M liters of scintillator  
instrumented with  
wavelength-shifting fibre and  
APDs



To 1 APD pixel

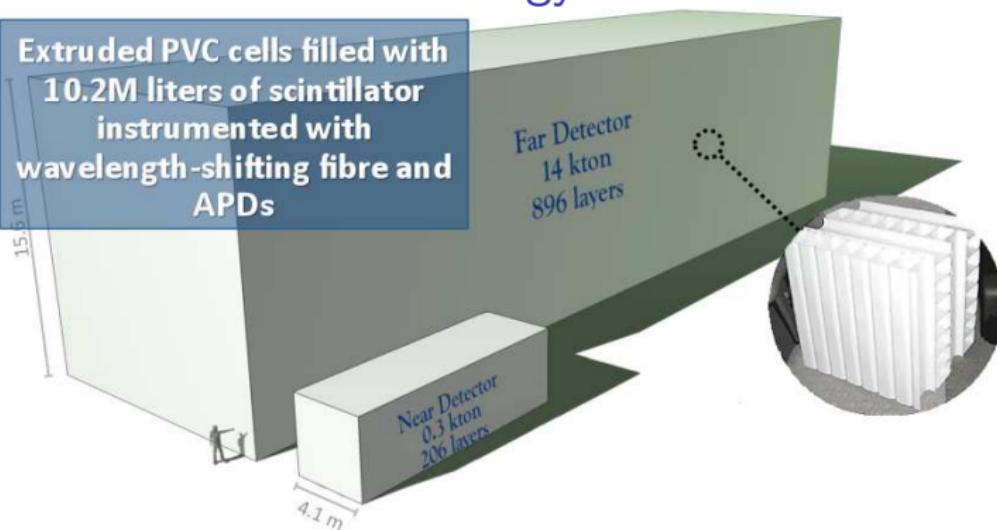


- ▶ Fine-grained low-Z, highly active, tracking calorimeter
- ▶ 64% liquid scintillator by mass
- ▶ WLS fibers looped in 4x6cm cells of PVC extrusion
- ▶ Each to one of 32 pixels of Hamamatsu APD

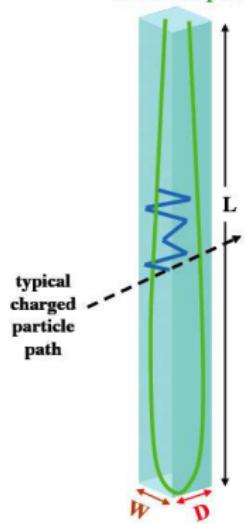


# NO $\nu$ A detector technology

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To 1 APD pixel



## Far Detector

- ▶ 14 kton
- ▶ 344,000 channels
- ▶ 810km from target
- ▶ Completed Aug 2014

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## Near Detector

- ▶ 0.3 kton
- ▶ 20,000 channels
- ▶ 1km from target
- ▶ Completed Aug 2014

NO $\nu$ A

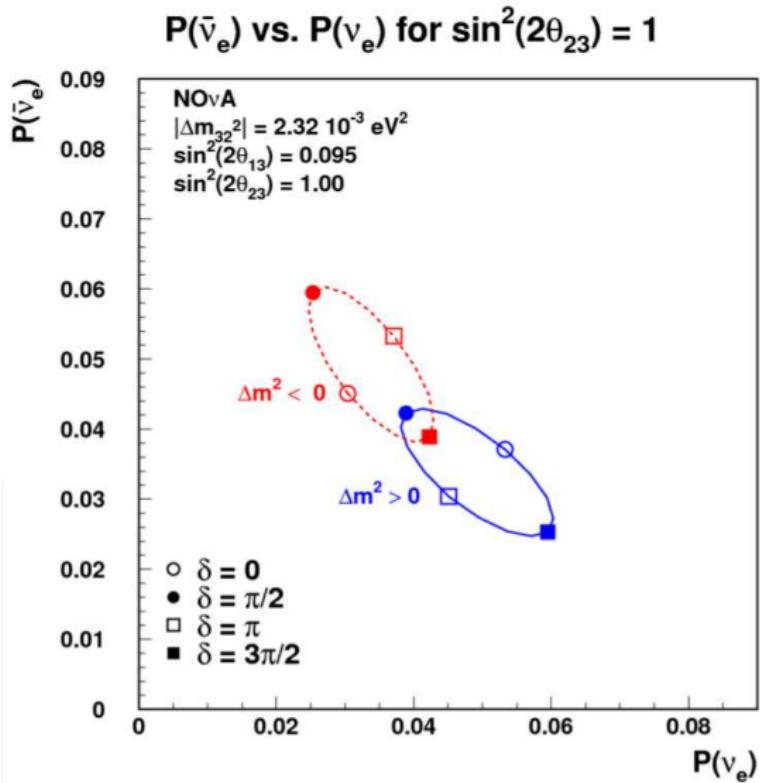


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# Principle of the $\nu_e$ measurement

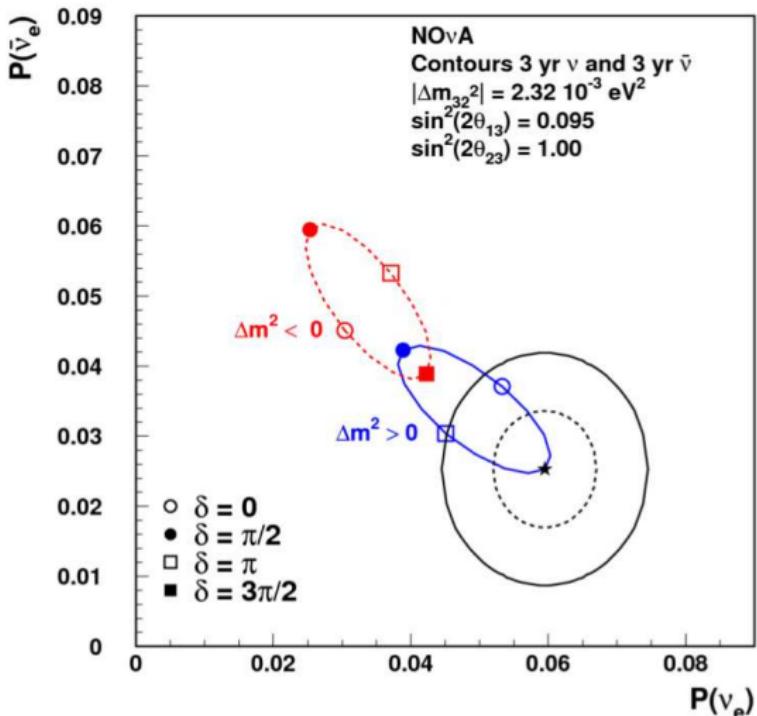
- ▶ To first order, NO $\nu$ A measures  $P(\nu_\mu \rightarrow \nu_e)$  and  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  evaluated at 2GeV
- ▶ These depend on normal/inverted hierarchy and  $\delta_{CP}$



# Principle of the $\nu_e$ measurement

- ▶ Measurements give an allowed region in this space
- ▶ In this case all inverted hierarchy scenarios are excluded at  $>2\sigma$

1 and 2  $\sigma$  Contours for Starred Point



# NO $\nu$ A sensitivities

- ▶ Assuming  $18 \times 10^{20}$  POT neutrinos +  $18 \times 10^{20}$  POT antineutrinos
  - ▶  $6 \times 10^{20}/\text{yr}$  for 3+3 years
- ▶ Assuming  $\sin^2 2\theta_{13} = 0.095$ ,  $\sin^2 2\theta_{23} = 0.95$  or 1.0
  - ▶  $\Delta m_{32}^2 = 2.35 \times 10^{-3} \text{ eV}^2$

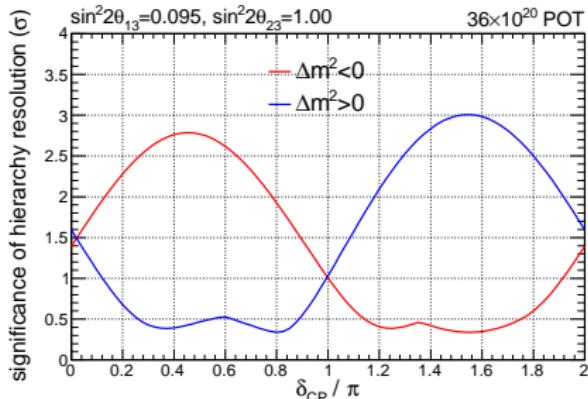
Representative event counts for analyses:

$\nu_e$ selected	$\nu$	$\bar{\nu}$
NC	19	10
$\nu_\mu$ CC	5	< 1
Beam $\nu_e$	8	5
Tot bkg	32	15
Signal	68	32

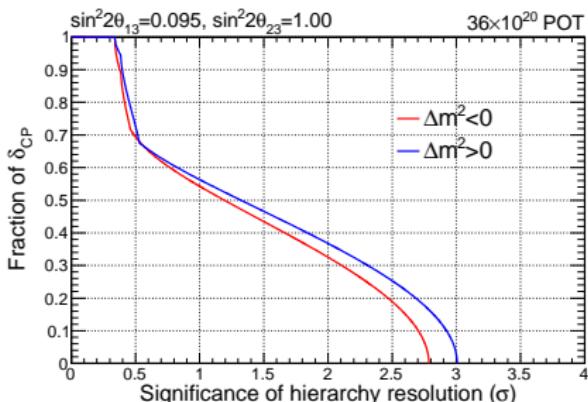
$\nu_\mu$ selected	$\nu$	$\bar{\nu}$
QE signal	82	49
NC bkg	< 1	< 1
non-QE signal	168	78
NC bkg	14	6
Uncont. signal	233	134
NC bkg	6	3
(0-5GeV visible energy)		

# Significance to resolve hierarchy/CPV

NOvA hierarchy resolution

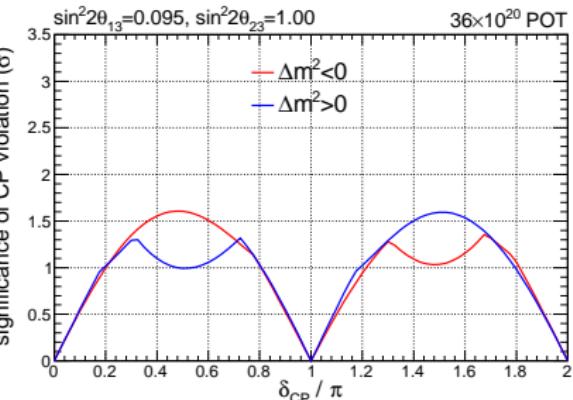


NOvA hierarchy resolution

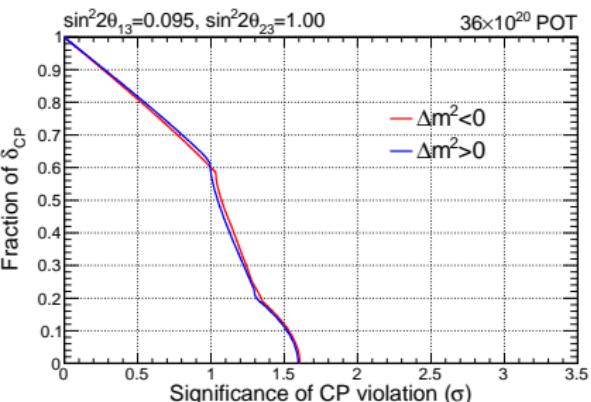


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NOvA CPV determination



NOvA CPV determination

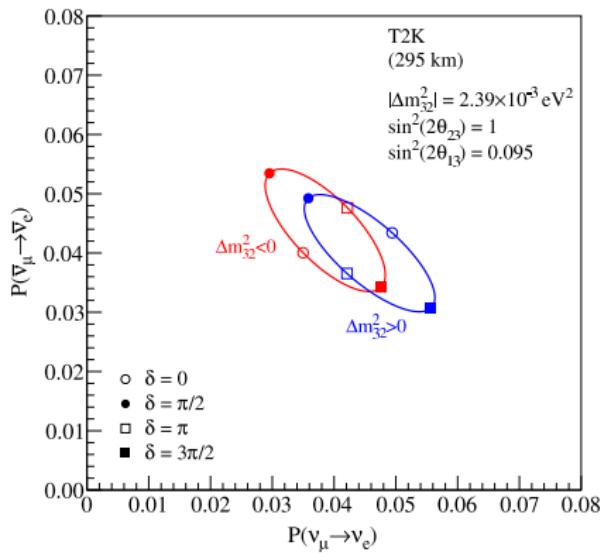


NOvA

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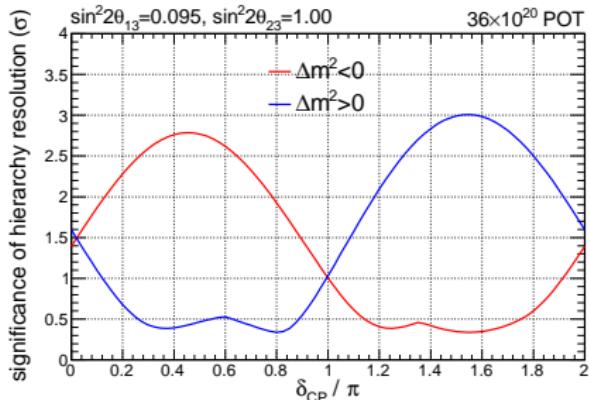
# T2K



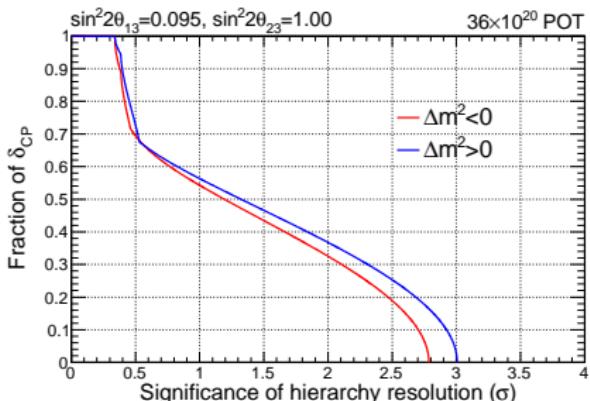
- ▶ T2K's 295km baseline → much smaller matter effects
- ▶ But exactly the same kind of CP sensitivity

# Significance to resolve hierarchy/CPV

NOvA hierarchy resolution

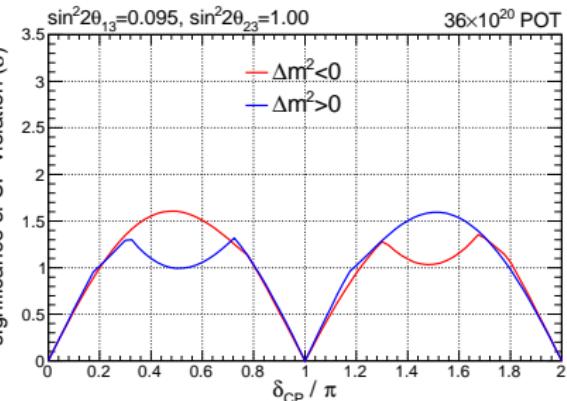


NOvA hierarchy resolution

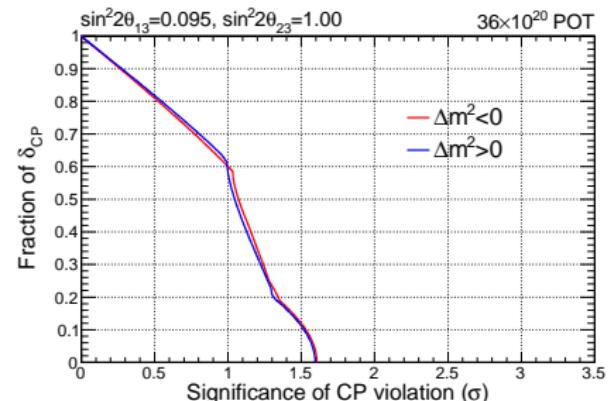


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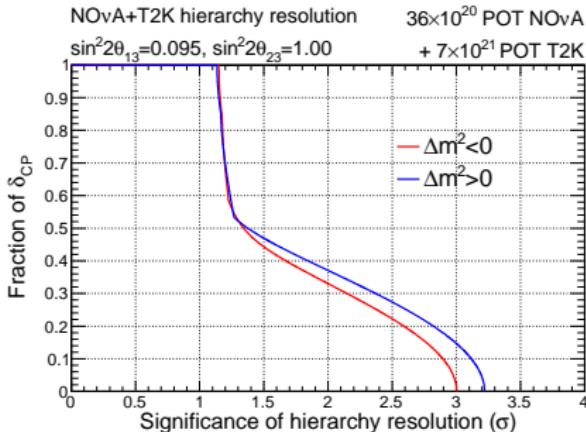
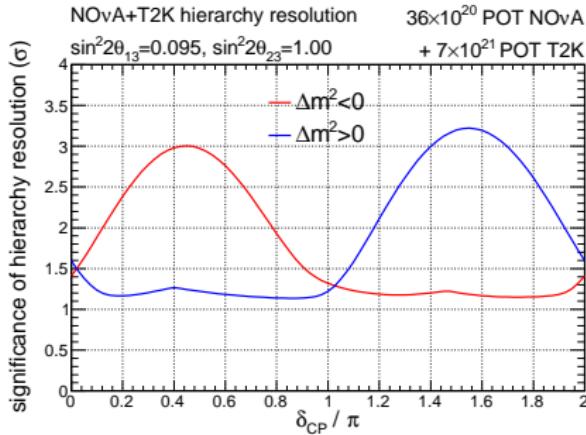


NOvA

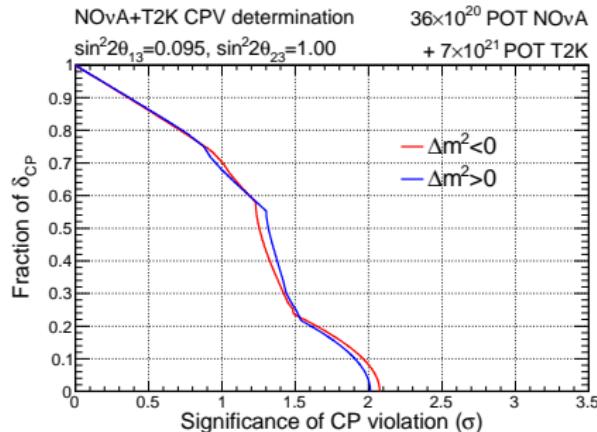
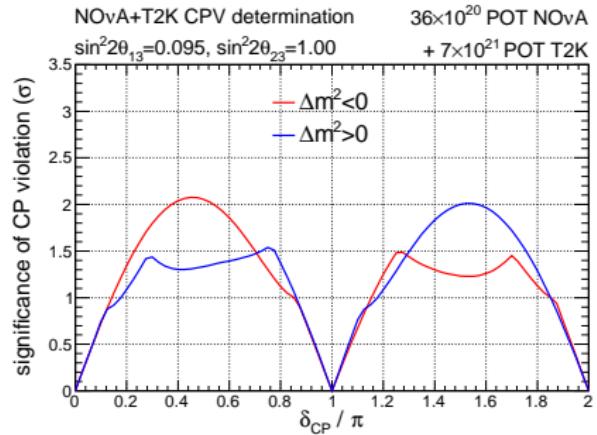
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# Significance to resolve hierarchy/CPV including T2K



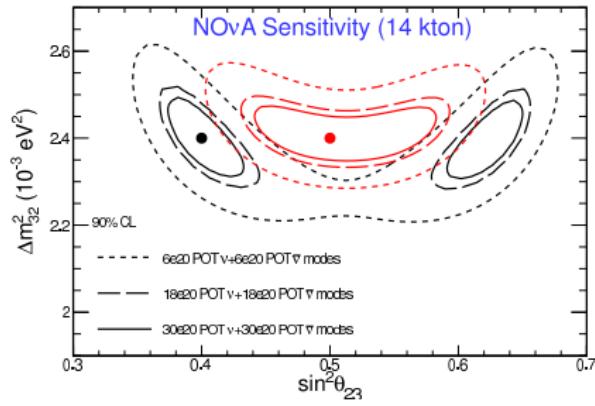
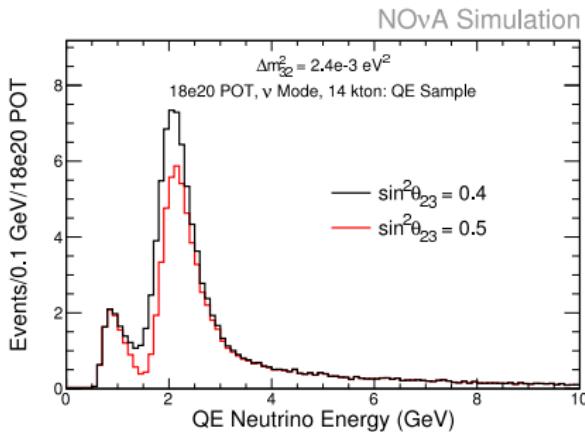
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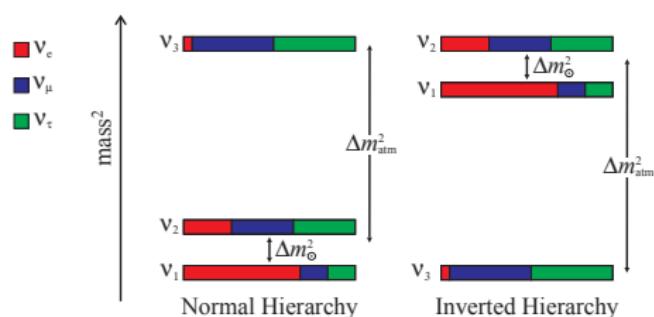
# $\nu_\mu$ analysis



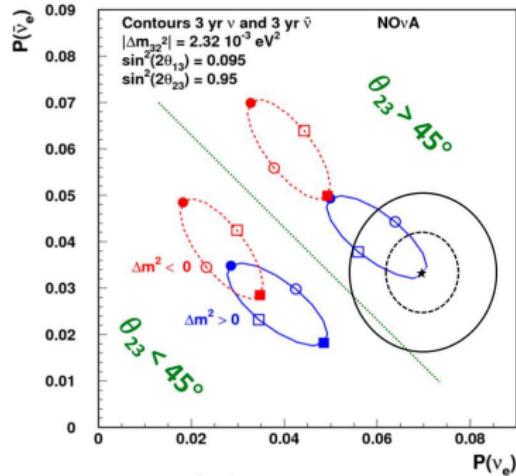
- ▶ Fit quasi-elastic, non-QE, and uncontained samples
- ▶ Percent level uncertainty on atmospheric parameters in 3+3 years
- ▶ Exclude maximal mixing at 90% in 1+1 years if  $\sin^2 2\theta = 0.95$

# Non-maximal mixing

- ▶ Maximal mixing is why the  $\nu_\mu$  and  $\nu_\tau$  contributions are the same size everywhere in this figure
- ▶  $\theta_{23} < 45^\circ$  means  $\nu_2$  is more  $\nu_\mu$
- ▶  $\theta_{23} > 45^\circ$  means  $\nu_3$  is more  $\nu_\mu$
- ▶  $\nu_e$  appearance at this baseline driven by  $\nu_3$ - $\nu_1$  splitting
- ▶ So beyond-maximal  $\theta_{23} \rightarrow$  more  $\nu_e$  appearance

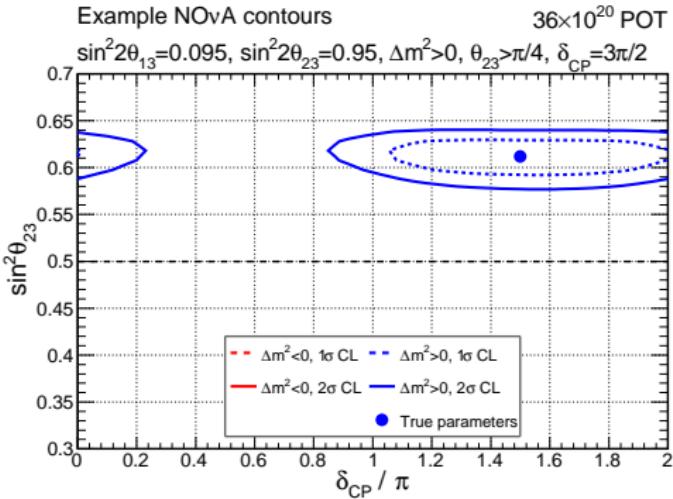
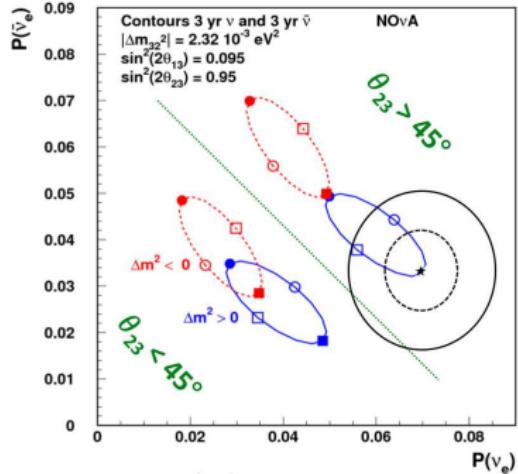


# Determining the octant of $\theta_{23}$



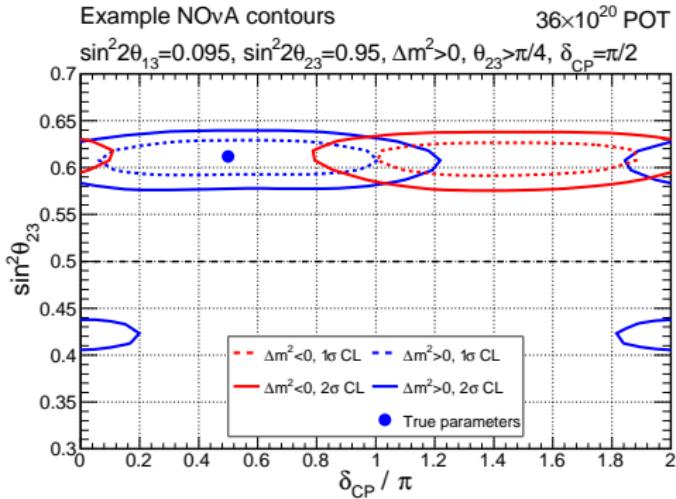
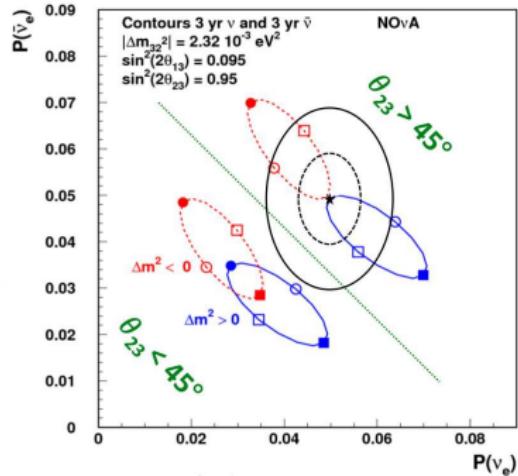
- If it turns out  $\theta_{23} \neq 45^\circ$ , is it bigger or smaller?
- Affects  $\nu_e$  probabilities. In same sense, contrasting with hierarchy and  $\delta_{CP}$ 's opposite sense

# Determining the octant of $\theta_{23}$



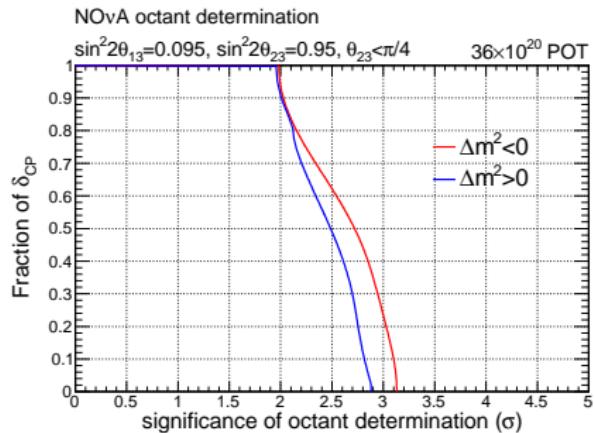
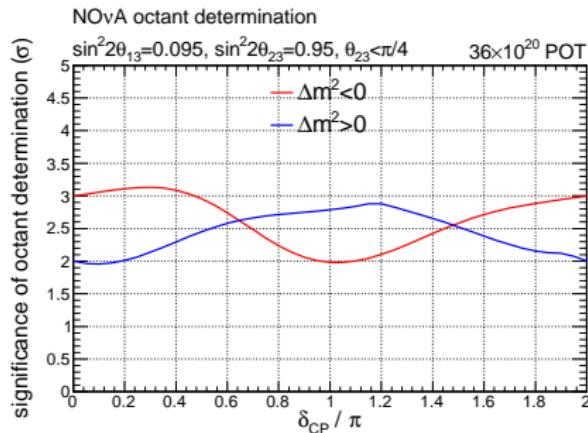
- If it turns out  $\theta_{23} \neq 45^\circ$ , is it bigger or smaller?
- Affects  $\nu_e$  probabilities. In same sense, contrasting with hierarchy and  $\delta_{CP}$ 's opposite sense
- Here we determine hierarchy and octant ( $>2\sigma$ ) and rule out half of  $\delta_{CP}$  space (at  $2\sigma$ )

# Determining the octant of $\theta_{23}$



- If it turns out  $\theta_{23} \neq 45^\circ$ , is it bigger or smaller?
- Affects  $\nu_e$  probabilities. In same sense, contrasting with hierarchy and  $\delta_{CP}$ 's opposite sense
- In a degenerate case hierarchy and  $\delta$  information are coupled, octant is not

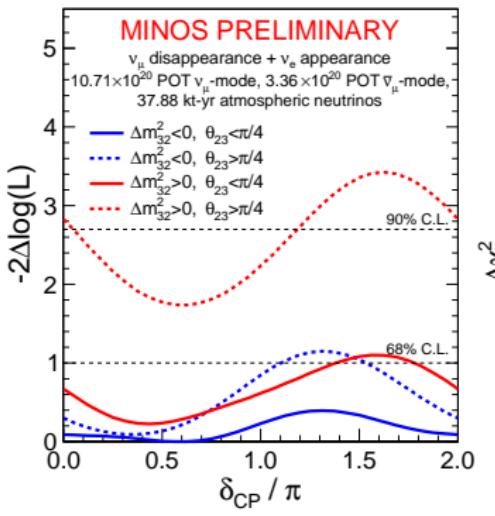
# Octant sensitivity



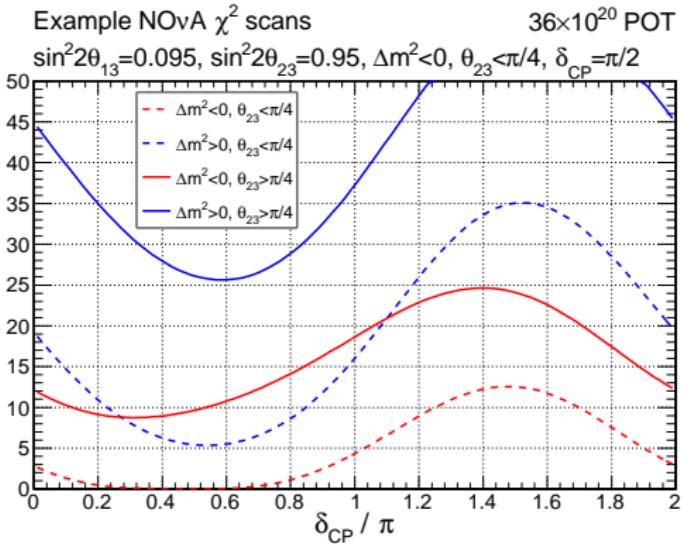
- ▶ Combine appearance and disappearance analyses
- ▶ For lower octant to match MINOS best-fit
- ▶ Upper octant slightly better

# Example $\Delta\chi^2$ scans

## MINOS result



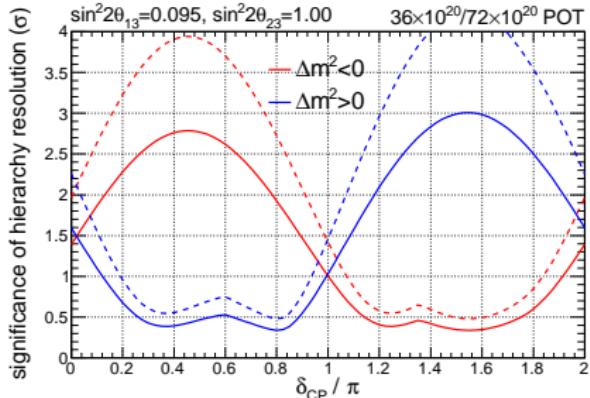
## NO $\nu$ A sensitivity



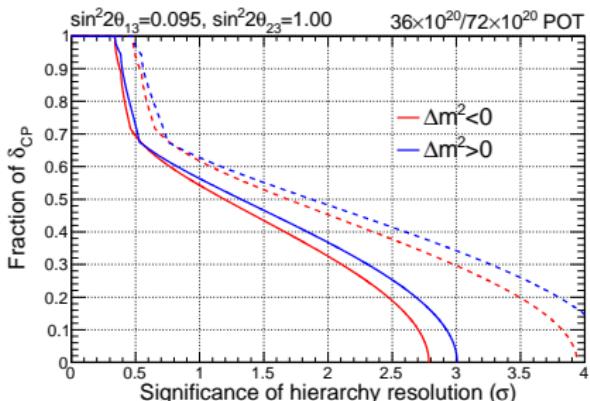
- Calculated For MINOS's best-fit parameters (IH, lower octant,  $\delta \sim \frac{\pi}{2}$ )
- Reject parts of phase-space at high confidence

# Significance to resolve hierarchy / CPV (2 $\times$ exposure)

NOvA hierarchy resolution

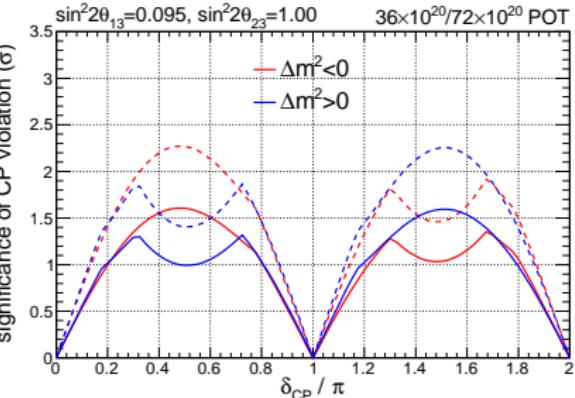


NOvA hierarchy resolution

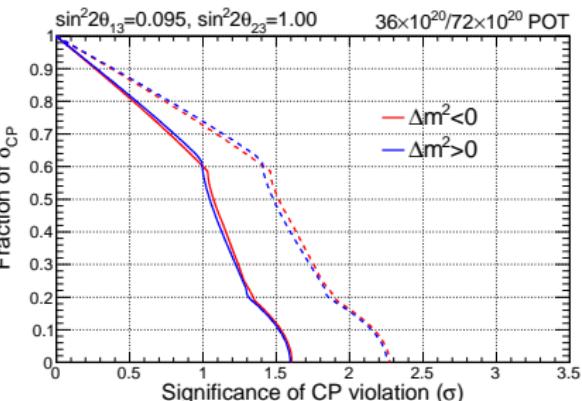


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NOvA CPV determination



NOvA CPV determination

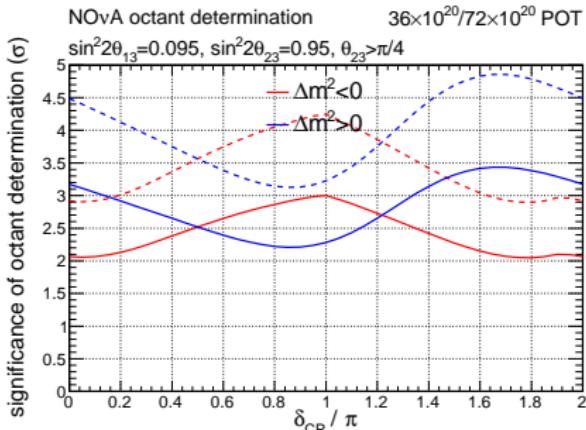
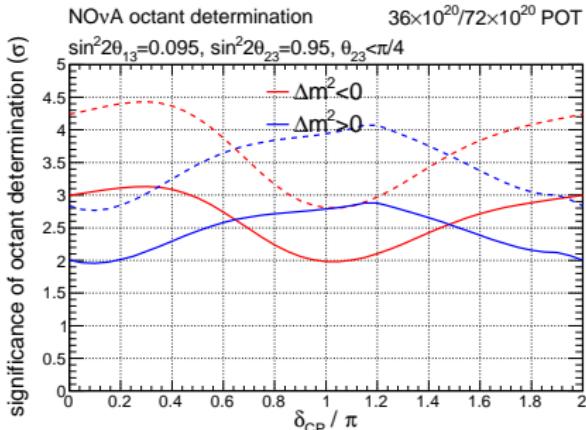


NOvA

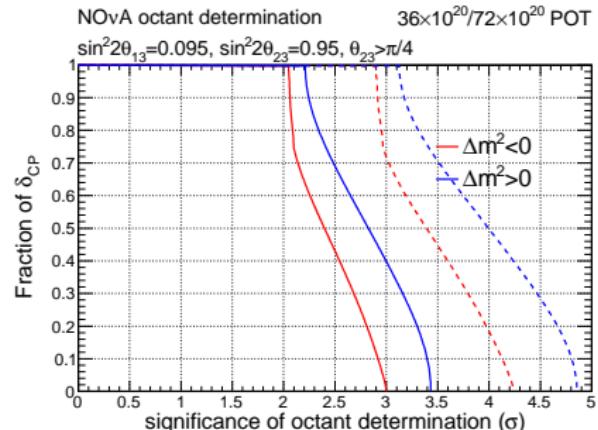
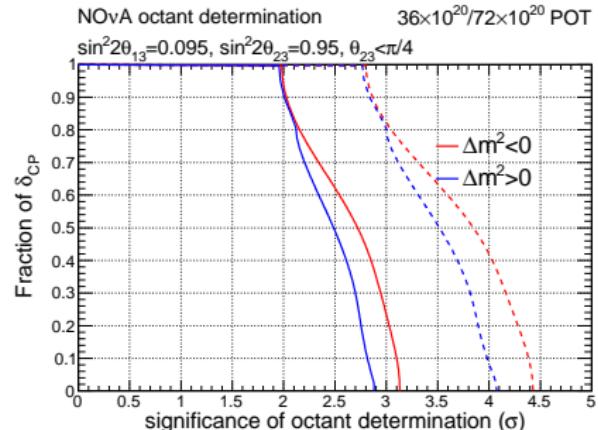
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# Octant sensitivity ( $2 \times$ exposure)



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## NO $\nu$ A sensitivity summary

- ▶ For sufficiently non-maximal  $\theta_{23}$ , good chance to determine octant
    - ▶ Essentially independent of other factors
  - ▶ Best case hierarchy determination  $3\sigma$ 
    - ▶ Very little sensitivity in degenerate case
  - ▶ Best case CPV discovery  $1.5\sigma$ 
    - ▶ Depends on value of  $\delta_{CP}$  (obviously)
  - ▶ Combination with T2K helps, but not a game-changer
  - ▶ In degenerate cases still provide good information, but statements on hierarchy and  $\delta_{CP}$  are coupled
- 
- ▶ NO $\nu$ A detectors and beam running well
  - ▶ Preparing for first analyses in the Spring

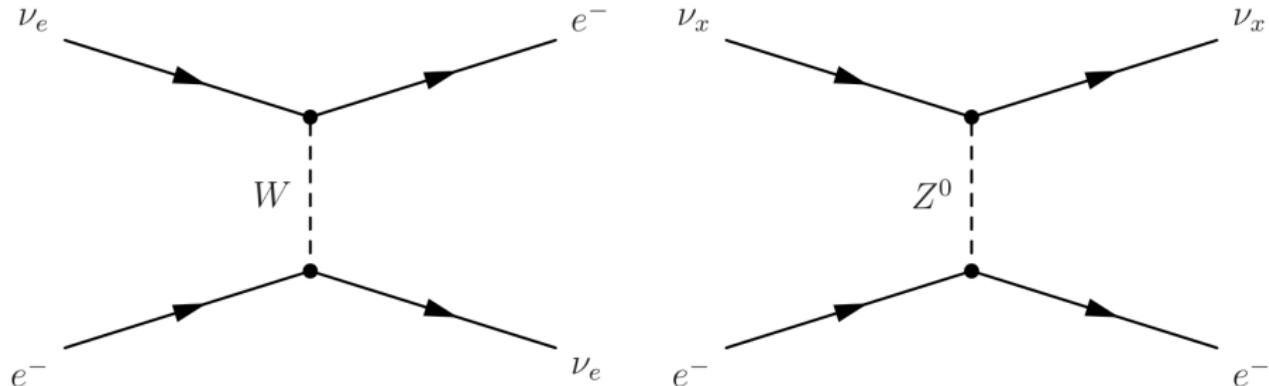


Thank you!

ROBER

# Backup

# Neutrino oscillations – matter effects

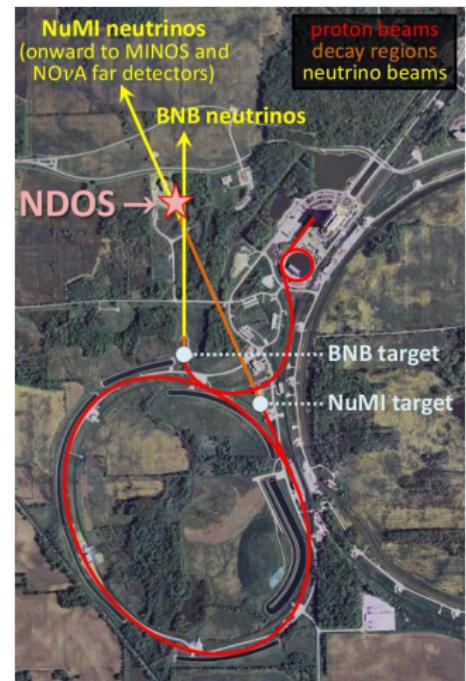
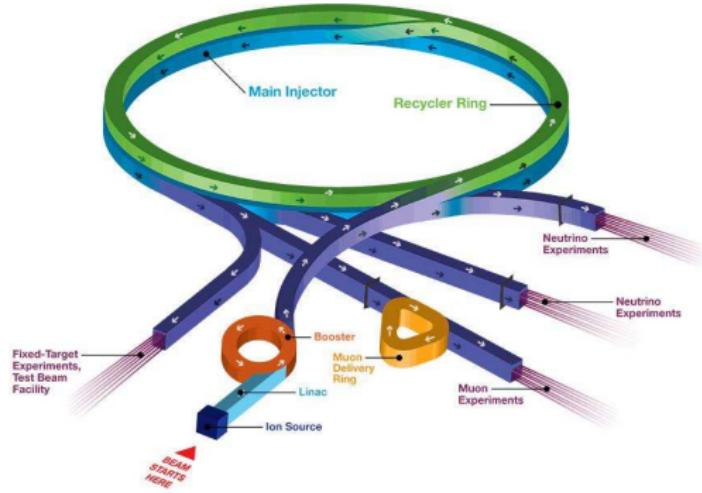


- ▶ Apparent source of CP violation (Earth is made of matter)
- ▶ CC interactions change effective mass of neutrinos
- ▶ Effect depends on hierarchy
  - ▶ Is the most- $\nu_e$  state the lightest, or one of the heaviest?

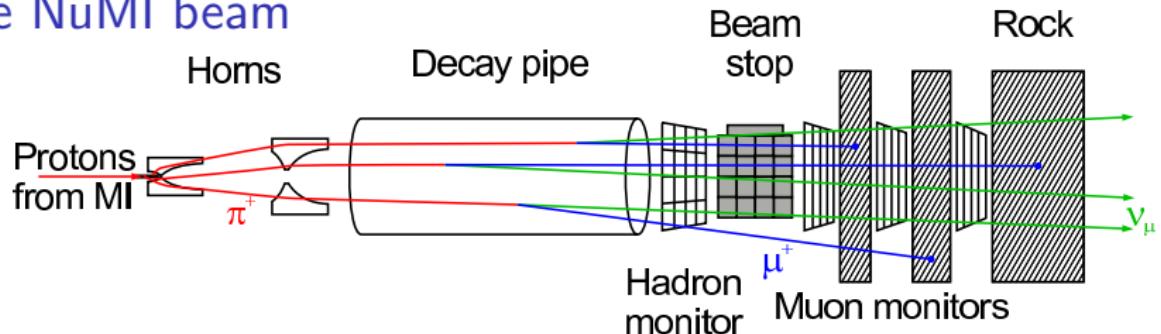
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta \mp 2\sqrt{2}EG_F N_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$
$$\tan 2\theta_M = \frac{\tan 2\theta}{1 \mp \frac{2\sqrt{2}EG_F N_e}{\Delta m^2 \cos 2\theta}}$$

# The NuMI beam

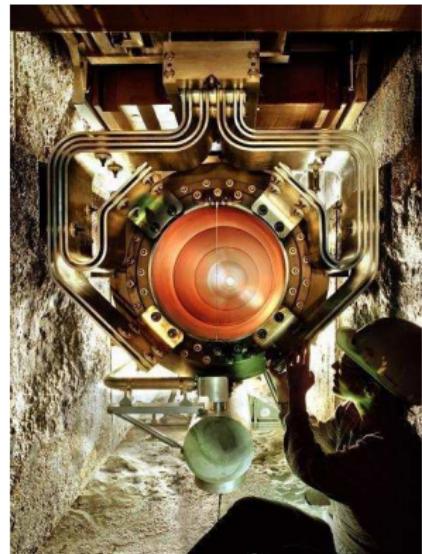
Fermilab Accelerator Complex



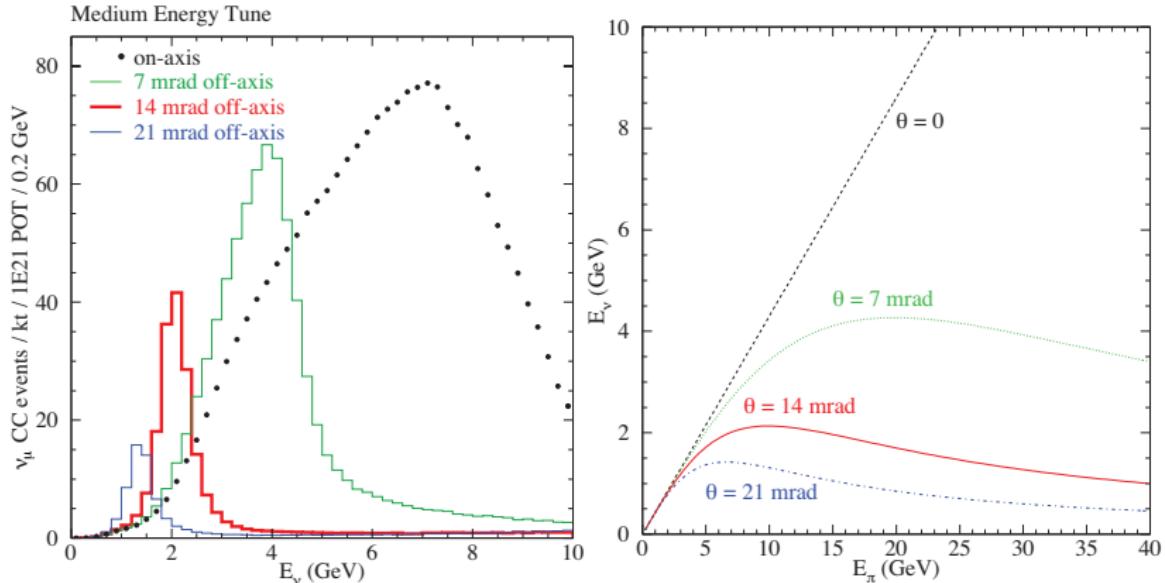
# The NuMI beam



- ▶ 120 GeV protons from the Main Injector
- ▶ Strike graphite target
- ▶ Produce hadrons. Primarily  $\pi^\pm$  and  $K^\pm$
- ▶ Focused by two magnetic horns
- ▶ Allow us to select charge sign for a neutrino or antineutrino beam
- ▶ 675m decay-pipe:  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- ▶ Muons absorbed by rock



# The NuMI beam – off-axis



$$\text{Flux} \sim \frac{1}{L^2} \left( \frac{1}{1 + \gamma^2 \theta^2} \right)^2$$

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

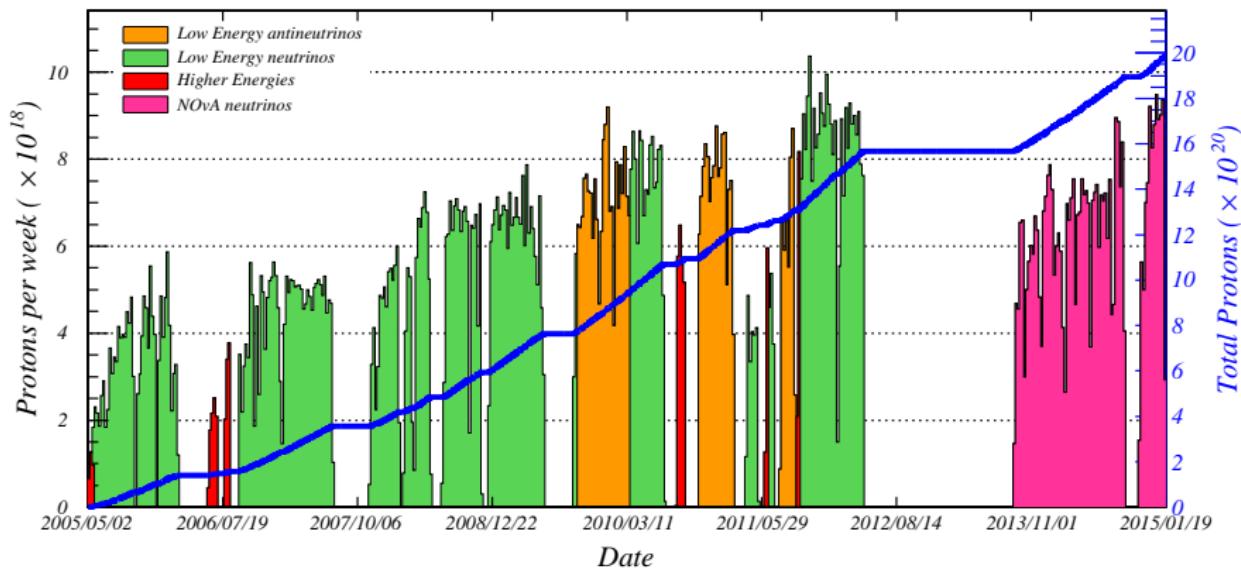
- Off-axis concept: neutrino energy  $\sim$  independent of pion energy
- $\rightarrow$  narrow-band beam, measure rate at oscillation max
- Reduce NC feed-down from high energy tail

# Accelerator and NuMI upgrades

- ▶ NuMI being upgraded from 350kW to 700kW
- ▶ Beam returned September 2013
- ▶ Convert Recycler to protons from antiprotons
- ▶ Shorten Main Injector cycle  $2.2\text{s} \rightarrow 1.33\text{s}$
- ▶ Overhaul of NuMI target station
- ▶ Goal of 400kW in 2015
- ▶ Maximum power 500kW until Booster RF upgrades completed

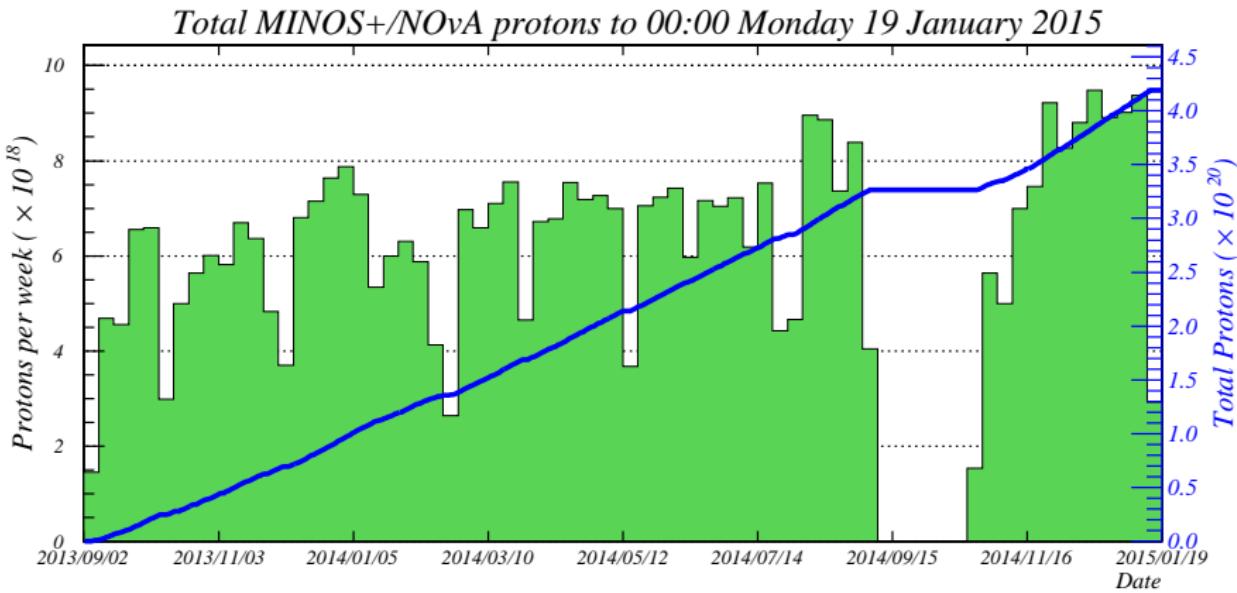


# NuMI performance

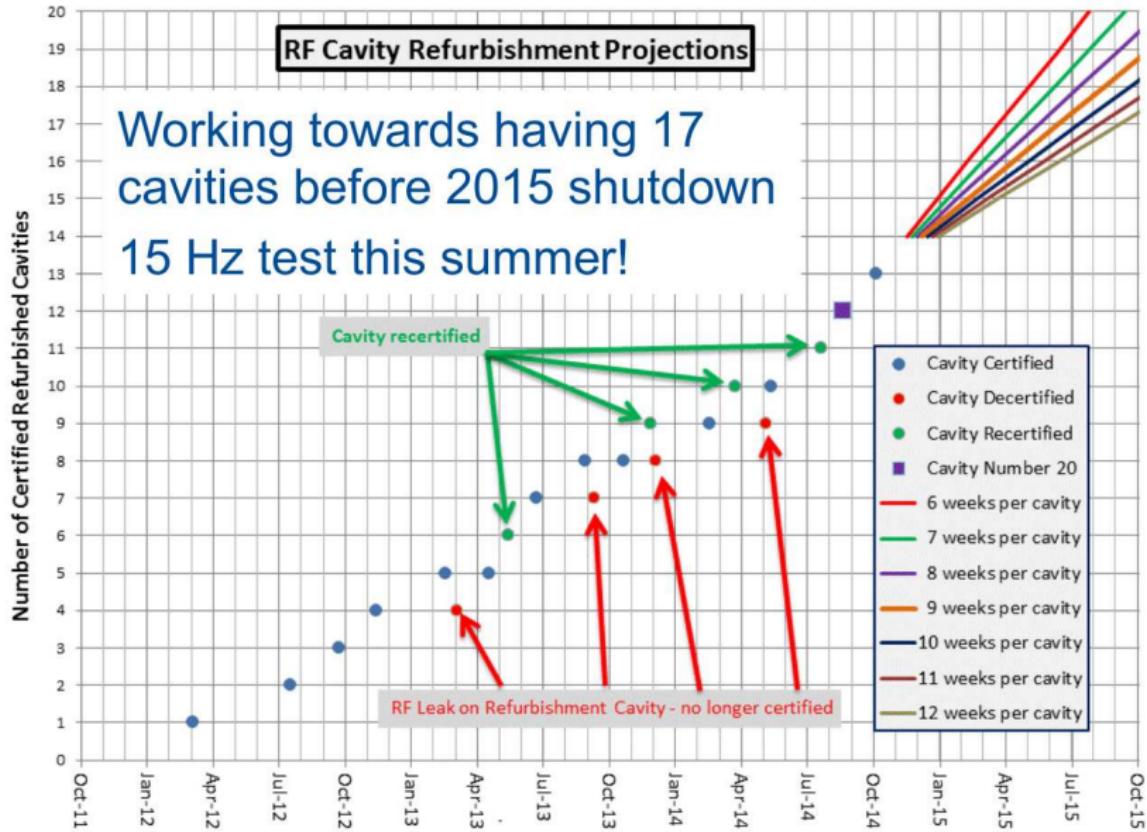


- ▶  $4.2 \times 10^{20}$  POT delivered to NO $\nu$ A
- ▶ Detector under construction during much of this period
- ▶ Equivalent to about  $10^{20}$  POT to full detector

# NuMI performance – NO $\nu$ A era



# RF cavity refurbishment projections



# Detector status



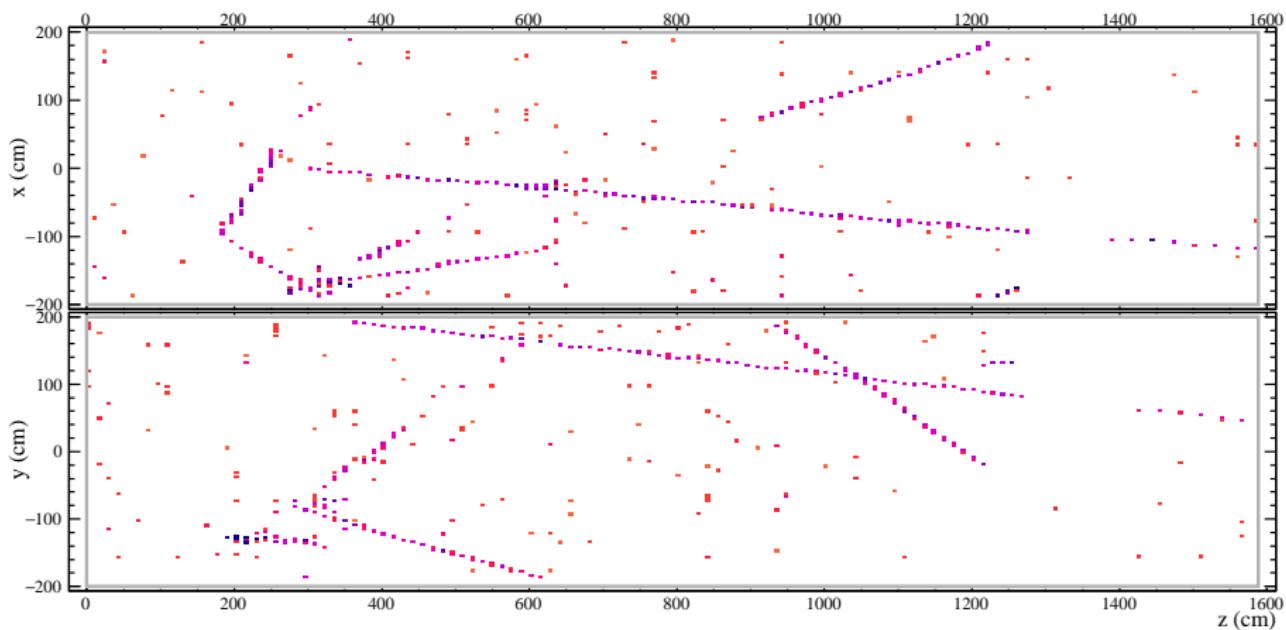
- ▶ FD Outfitting completed August 2014, passed CD4 review
- ▶ ND completed August 2014

## Detector status



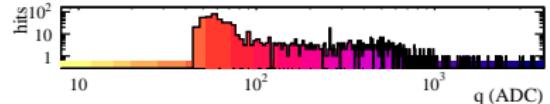
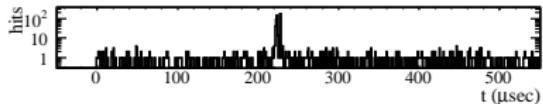
- ▶ FD Outfitting completed August 2014, passed CD4 review
- ▶ ND completed August 2014

# ND neutrinos

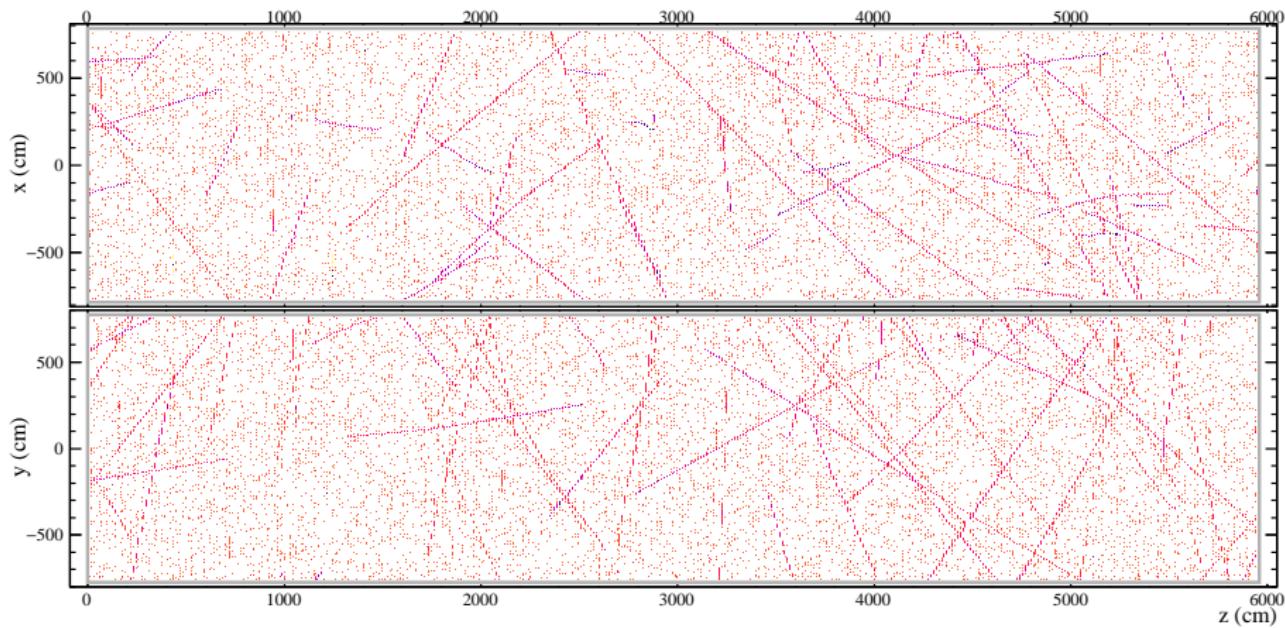


NOvA - FNAL E929

Run: 10498 / 14  
Event: 1608875 / NuMI  
UTC Sat Oct 25, 2014  
19:22:54.765851648

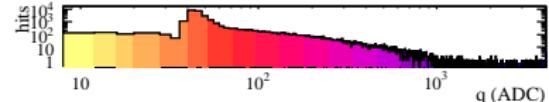
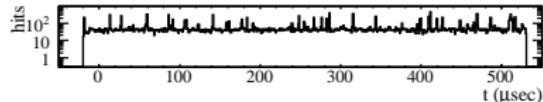


# FD cosmic rays

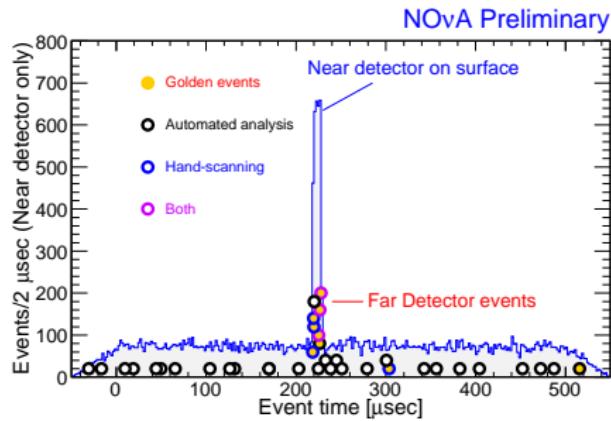
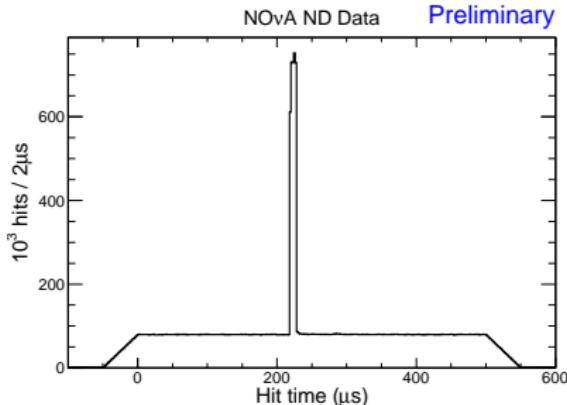


NO $\nu$ A - FNAL E929

Run: 18638 / 29  
Event: 379290 / NuMI  
UTC Sun Jan 11, 2015  
13:05:7.741219200

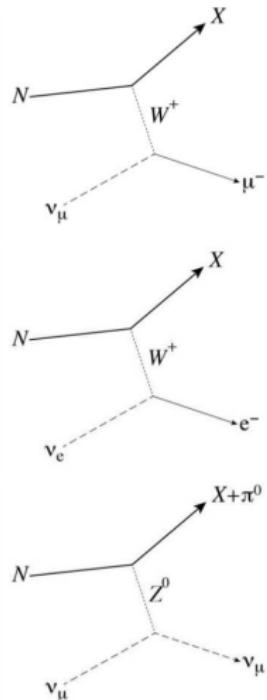
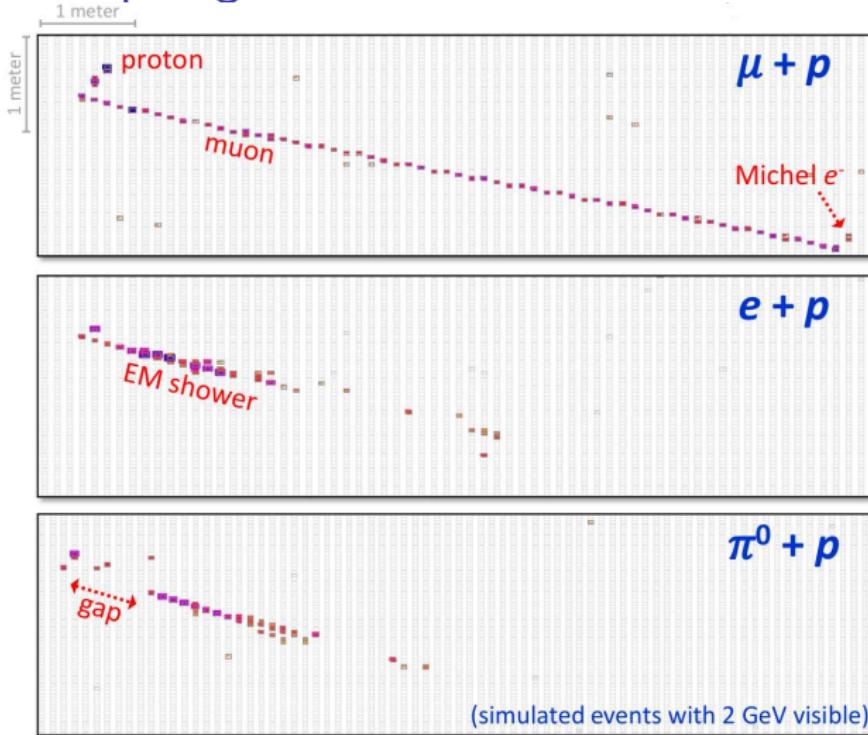


# Beam peaks



- ▶ ND and FD beam peaks - we see neutrinos!
- ▶ Validates timing synchronization
- ▶ Hand-scan plus automated methods in FD
- ▶ Now fully automated

# Event topologies



- ▶ Very good granularity, especially considering scale
- ▶  $X_0 = 38\text{cm}$  (6 cell depths, 10 cell widths)

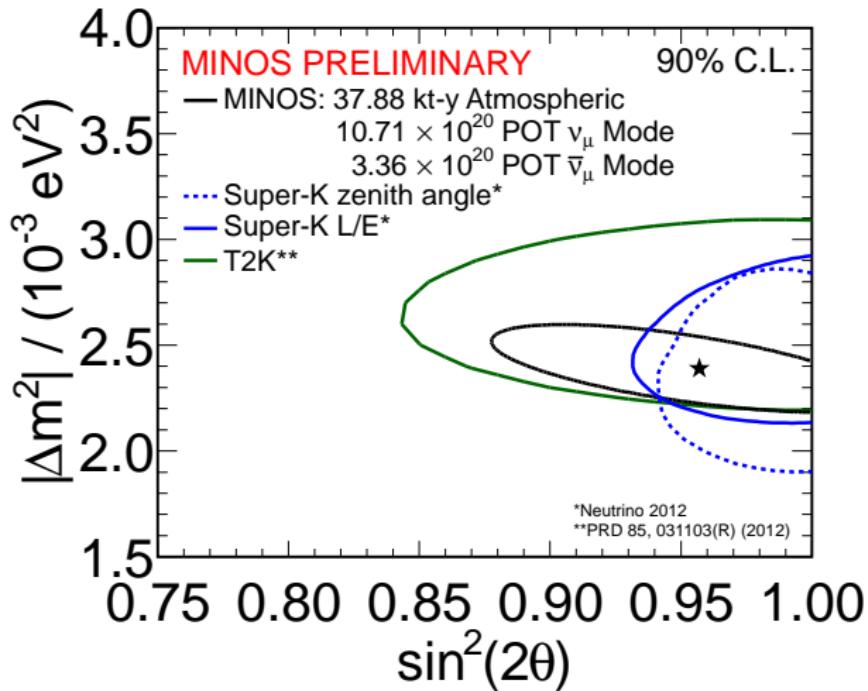
# Far Detector building



# Assembly

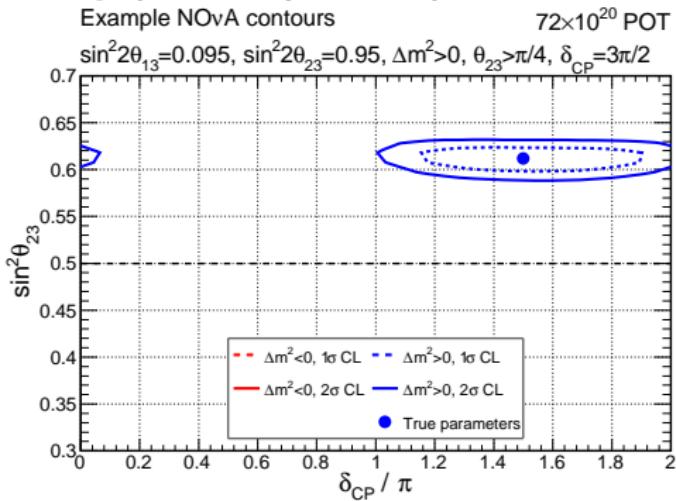
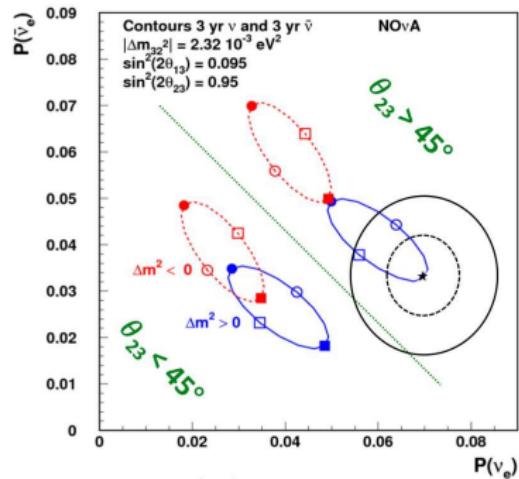


## $\nu_\mu$ analysis



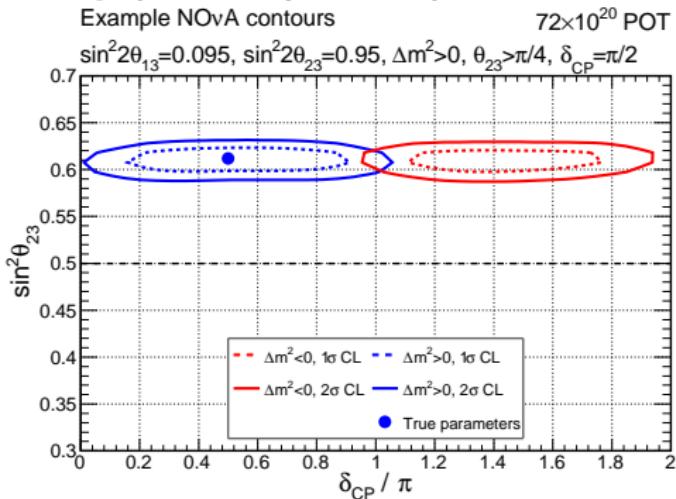
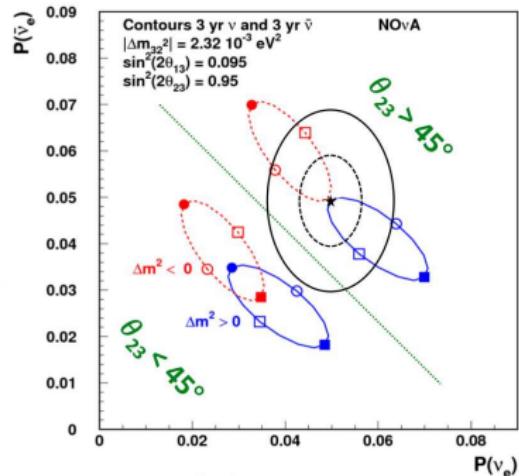
- ▶ Current constraints on  $\sin^2 2\theta_{23} \gtrsim 0.9$
- ▶ Hints of non-maximal value from MINOS

# Determining the octant of $\theta_{23}$ ( $2\times$ exposure)



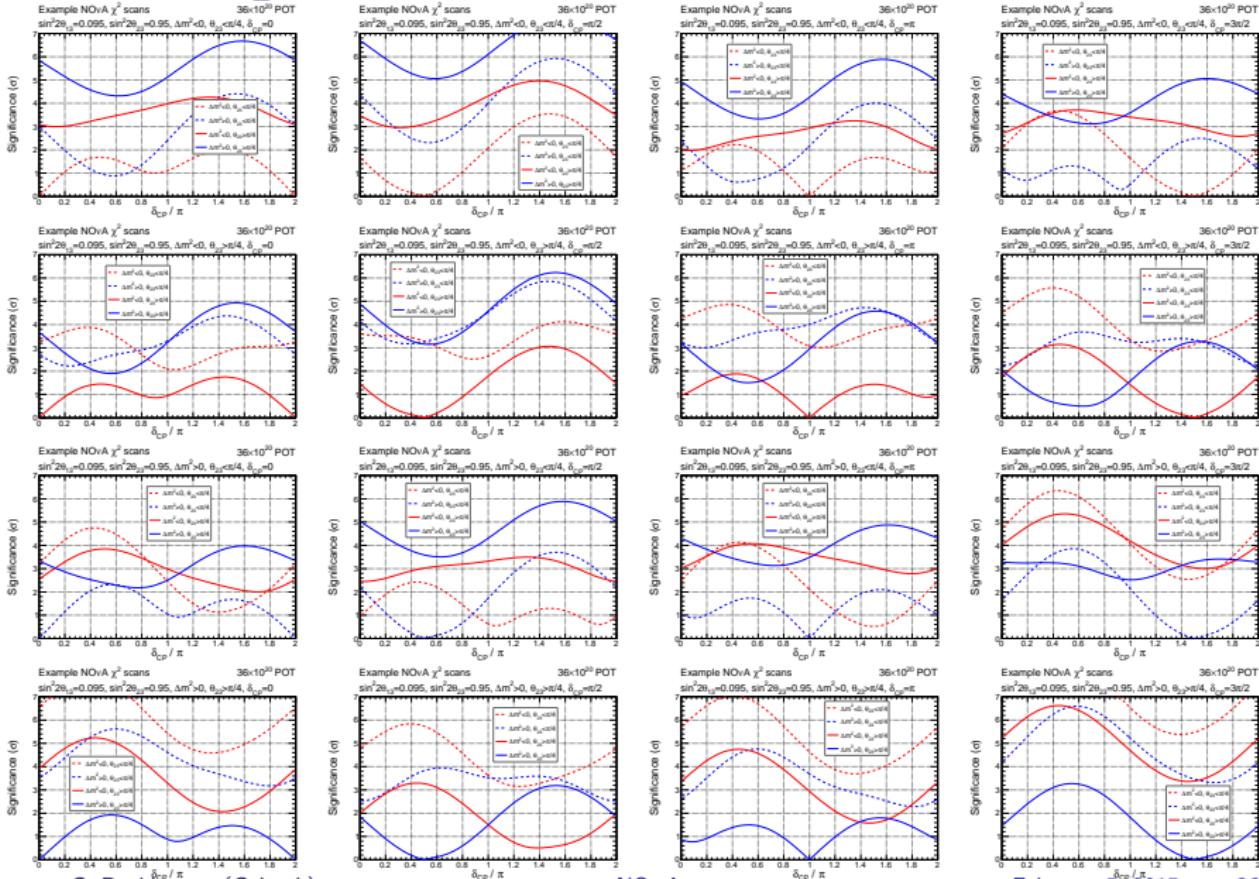
- If it turns out  $\theta_{23} \neq 45^\circ$ , is it bigger or smaller?
- Affects  $\nu_e$  probabilities. In same sense, contrasting with hierarchy and  $\delta_{CP}$ 's opposite sense
- Here we determine hierarchy and octant ( $>2\sigma$ ) and rule out half of  $\delta_{CP}$  space (at  $2\sigma$ )

# Determining the octant of $\theta_{23}$ ( $2 \times$ exposure)

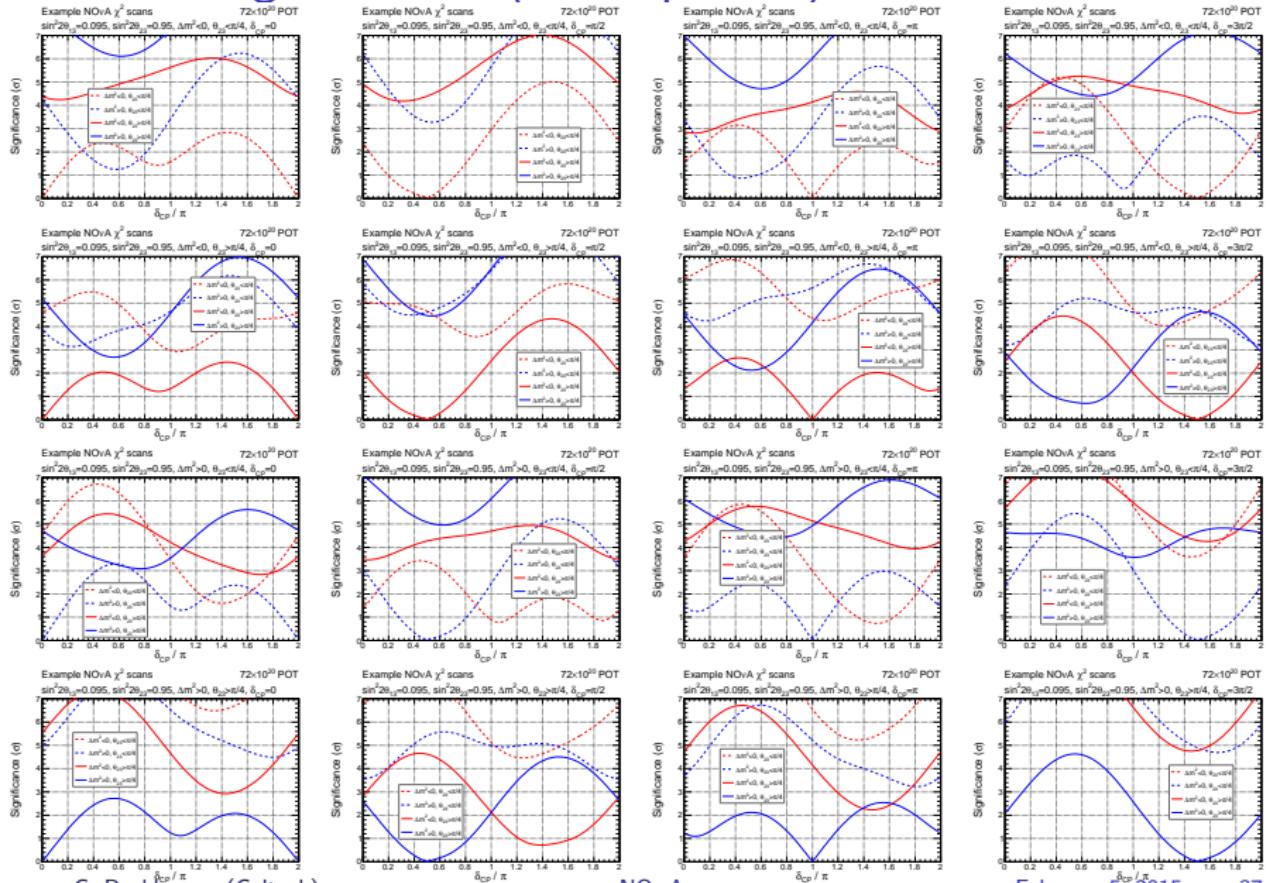


- If it turns out  $\theta_{23} \neq 45^\circ$ , is it bigger or smaller?
- Affects  $\nu_e$  probabilities. In same sense, contrasting with hierarchy and  $\delta_{CP}$ 's opposite sense
- In a degenerate case hierarchy and  $\delta$  information are coupled, octant is not

# $\delta$ slices – significances



# $\delta$ slices – significances ( $2 \times$ exposure)



C. Backhouse (Caltech)

NOvA

February 5, 2015

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